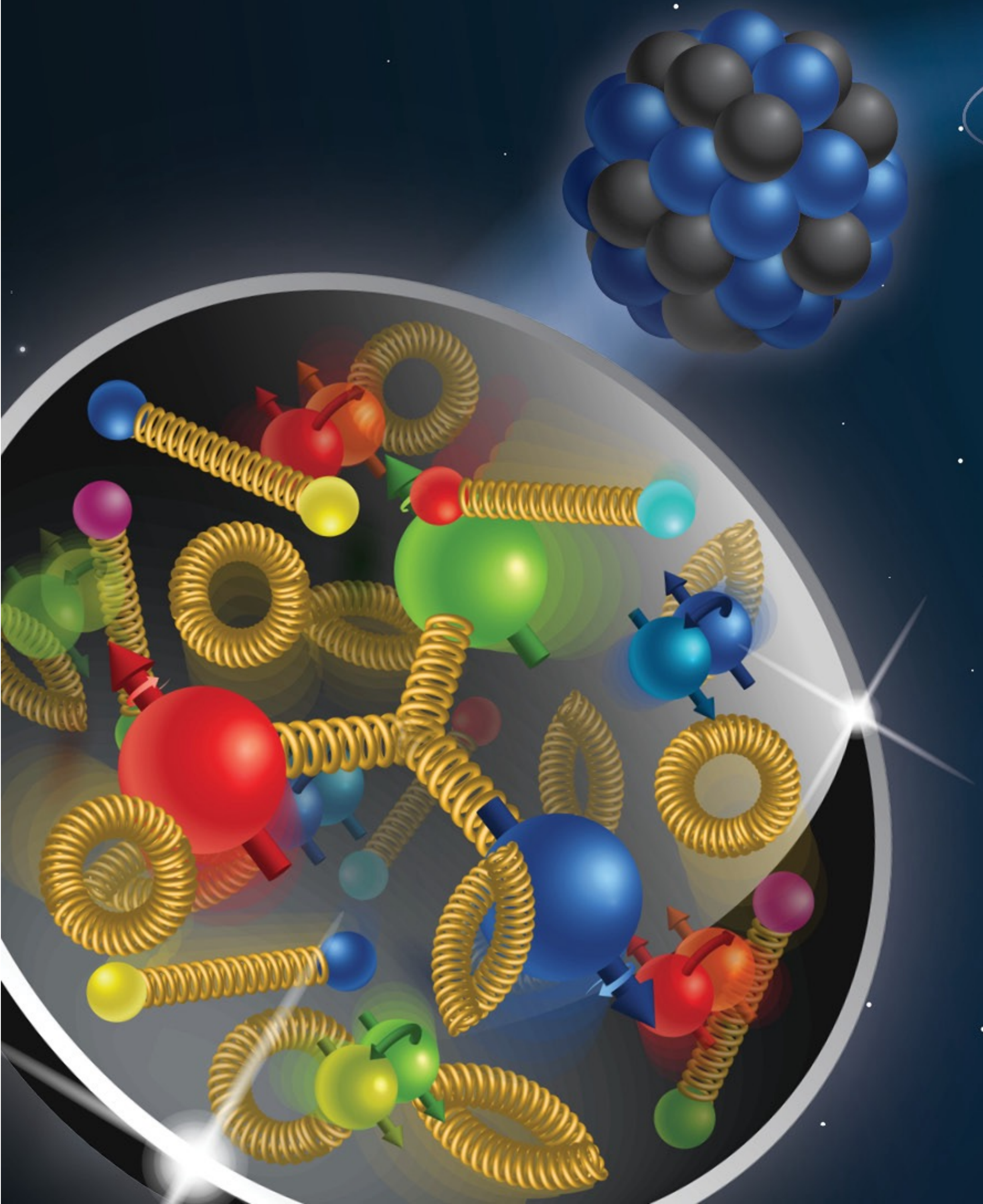
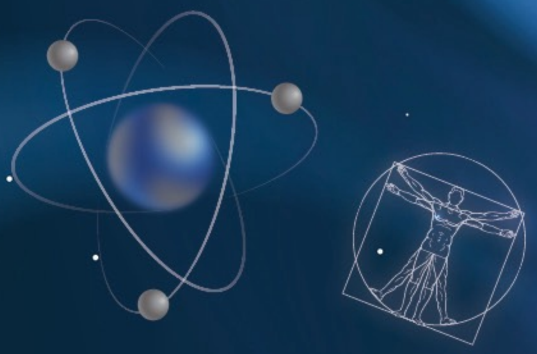




EIC Instrumentation Challenges

David Gassner Sept 14, 2022

eeFACT22

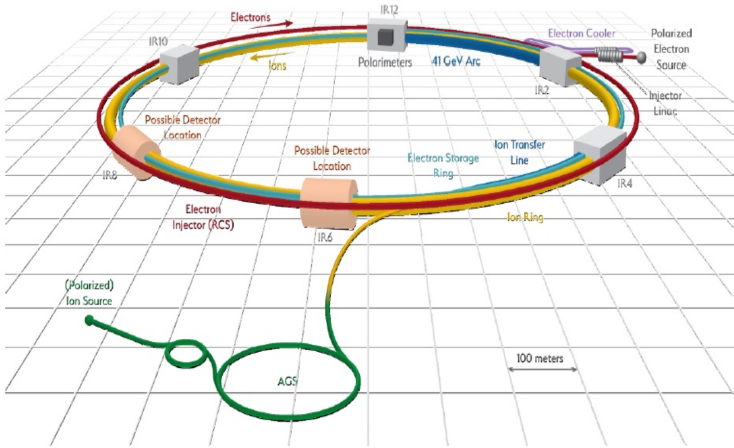
Electron-Ion Collider

Brookhaven National Laboratory · Jefferson Lab · U.S. Department of Energy Office of Science

Outline

- EIC Overview
- General instrumentation challenges
- Selected instrumentation technical challenges
    - Individual bunch position measurements (short bunch spacing)
        - Electron Storage Ring injection
        - Strong Hadron Cooling ERL
    - Crabbing angle measurements
        - Electron crabbing angle measurements using synchrotron light monitor
        - Hadron crabbing angle measurement BPM near IP
        - Hadron residual crabbing angle monitor
    - Hadron Ring
        - New cryo-BPM pick-ups
    - Interaction Region
        - Cryo BPMs and large aperture BPMs
    - Strong Hadron Cooling
        - Relative longitudinal bunch alignment to ~ 1 micron
- Summary

Electron Ion Collider Overview



- Brief overview of EIC machines regions:
  - Pre-Injector (polarized electrons)
    - Turn-key 400 MeV Linac, 7 nC bunches
    - Photocathode electron gun, and beam transports provided by BNL
    - All beam instrumentation by BNL
  - Rapid Cycling Synchrotron (similarities to light source booster)
    - 3.8 km, Inject at 400 MeV, accelerate to 5, 10 or 18 GeV, 100 ms acceleration ramp, 1 Hz rate. Bunch merging (7 to 14 to 28 nC)
  - Electron Storage Ring (similarities light source storage ring)
    - 3.8 km, 5, 10 & 18 GeV, 2.5 Amps, 1,160 bunches, 10 ns bunch spacing, 28 nC, 7 mm RMS bunches, one bunch replaced each second
  - Hadron Ring Instrumentation Upgrade
    - 3.8 km, 41 to 275 GeV store energies, 1 Amp, up to 1,160 bunches, 10 ns bunch spacing, 30 nC/bunch, 6 cm RMS bunch length
    - All established RHIC instrumentation systems will be upgraded for the shorter, higher intensity bunches, and the beam line components will be relocated to new locations in tunnel
      - New lower impedance beam line components
      - New electronics
  - Interaction Region
    - IP collision feedback systems, crabbing angle measurements, beam loss monitors
  - Strong Hadron Cooling
    - Single pass electron machine (~ 400 m of beam transport), 1 nC, 10 ps RMS bunches, 10 ns spacing, 100 mA average current, up to 150 MeV

EIC Instrumentation General Challenges

- Challenges related to large scale accelerator projects
  - Largest System - Beam Position Monitors
    - 7 machines regions, each with unique requirements
    - ~ 1,660 BPMs
  - About 700 other new instruments throughout the facility, see next slide
- Complications related to the pandemic
  - Supply chain delays & global chip shortages
    - At the present EIC preliminary design phase, very long delays in obtaining electronic components for prototype assembly and testing.
    - If these delays continue into the construction phase, can delay project completion schedule
  - Providing accurate materials cost estimates
    - Potential artificially inflated cost estimates due to inflation and other factors makes it difficult to provide accurate long term budgetary plans.
  - Maintaining adequate staffing
    - Elevated number of senior employees left or may be leaving soon
    - Challenging to find new hires with experience
    - Instrumentation staff is matrixed with with existing Collider-Accelerator department until 2025

EIC Instrumentation Scope

Electron Storage Ring

Instrument	Quantity
BPMs	494
BLMs	50
DCCT/FCT	2
Synch Light Mon	2
X-Ray Pin-hole	1
Tune Monitor	1
Polarimeter	1
Trans BbB FB	1
Long BbB FB	1
Slow Orbit FB	1
BBA	1

Hadron Storage Ring

Instrument	Quantity
BPMs	279
BLMs	220
IPM	2
Longi Prof Mon	1
Tune Monitors	2
DCCT	1
HF Schottky	1
LF Schottky	1
HT pick-up	1
Global Orb FB	1
Polarimeter	2
BbB Damper	1

Rapid Cycling Synchrotron

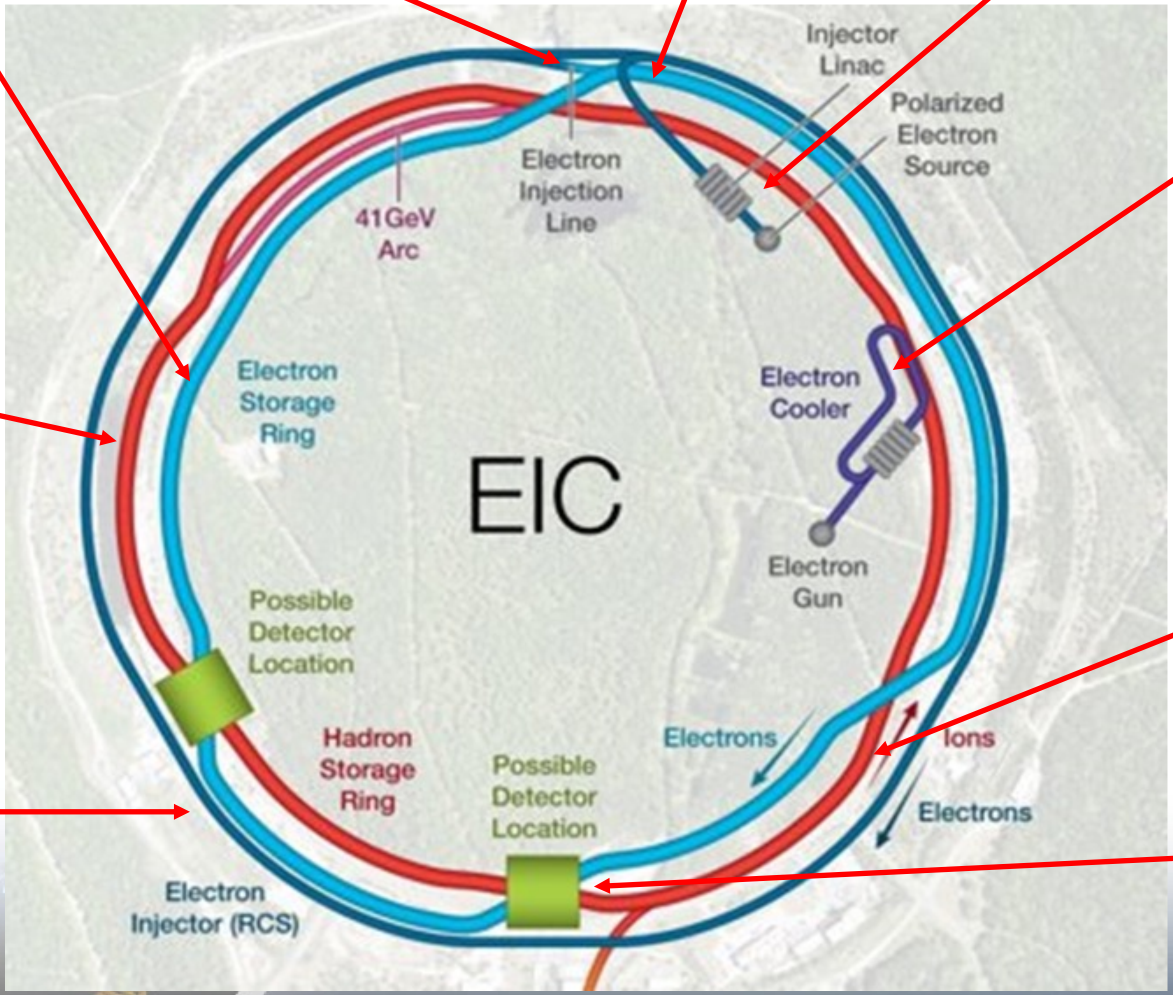
Instrument	Quantity
BPMs	576
BLMs	20
DCCT/FCT	2
Profile Mon's	7
Synch Light Mon	2
Tune Monitor	1
BBA	1

RCS to ESR Transport

Instrument	Quantity
BPMs	22
Prof Mon's	7
Charge Mon's	2

Pre-Inj Linac to RCS Transport

Instrument	Quantity
BPMs	30
Prof Mon's	7
Charge Mon's	2



Hadron Injection from AGS

Electron Pre-Injector (400 MeV)

Instrument	Quantity
BPMs	13
YAG/OTR Mon's	13
Charge Mon's	10
BLMs	4
Faraday Cup	2
Bunch Length	2
Emittance Mon	1
Mott Polarimeter	2

Strong Hadron Cooling

Instrument	Quantity
BPMs	110
BLMs	88
Beam Pipe Temp Mon's	70
Screen Prof Mon's	35
Current & Charge Mon's	18
Faraday Cups	12
Wire scanners	9
Emittance Mon's	7
Halo Mon's	4
Transverse Defl Cavity	1
Synch Light Mon's	4
Relative Bunch Alignment	1

HSR Injection Transport

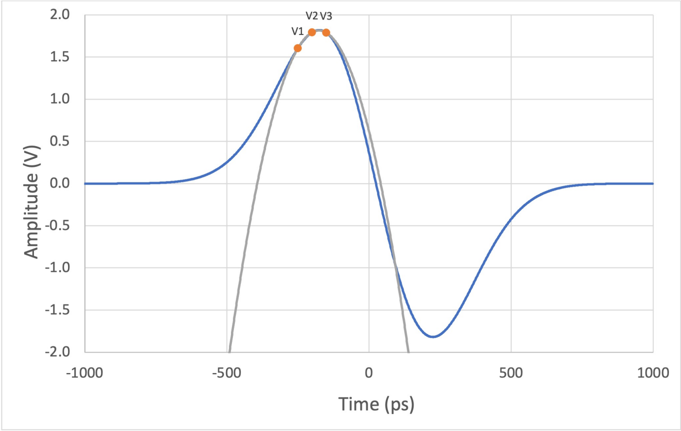
Instrument	Quantity
BPMs	41
BLMs	20
Profile Mon's	6
Charge Mon's	2

Interaction Region

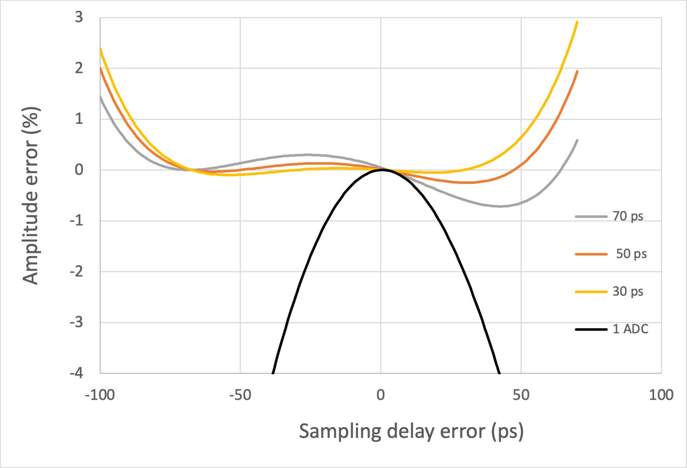
Instrument	Quantity
BPMs	78
BLMs	50
Orbit Corr at IP	2
Crab Tilt Monitor	1

Individual bunch position measurement with short bunch spacing, 2 cases

- **At ESR Injection, bunch replacement at 1 Hz, with a ring filled with 1,160 bunches**
  - Electron bunch spacing is 10 ns
  - Need to measure injected bunch position in the presence of adjacent stored bunches, only at the first 20 BPMs after injection
  - Ensure injected bunch trajectory is correct
- **Strong Hadron Cooling, Energy Recovery Linac**
  - Electron bunch spacing is 5 ns
  - Alternating bunches are accelerating and decelerating, BPMs are located between Linac cavities.
  - Need to measure individual bunch positions in the presence of adjacent bunches
- Considering using 3 digitizers each triggered at determined intervals, then use parabolic fit to reduce the measurement uncertainty due to ADC timing jitter.

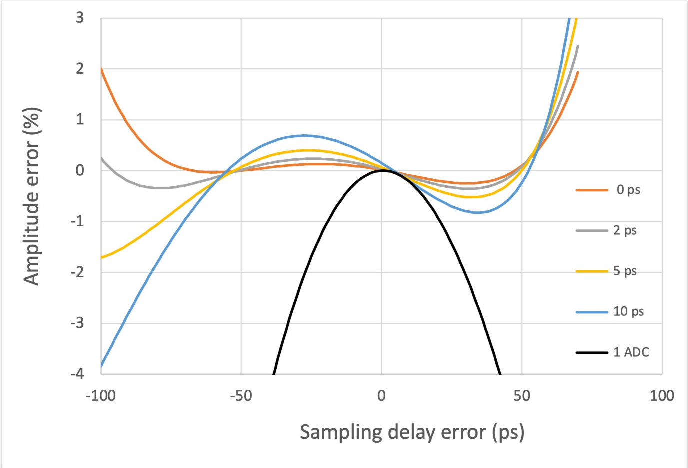


The result of a simulated signal from a BPM traversed by an ultra-relativistic gaussian bunch with an RMS length of 200 ps (60 mm) is shown in Fig. 1. The parabola determined by the three voltages sampled at 50 ps intervals has an apex of 1.8153 V while the peak amplitude of the BPM signal is 1.8195, a 0.23% difference for a sampling delay error of 20 ps.



Performance comparison with three different sampling intervals: 30 ps, 50 ps and 70 ps

Black line is single ADC error



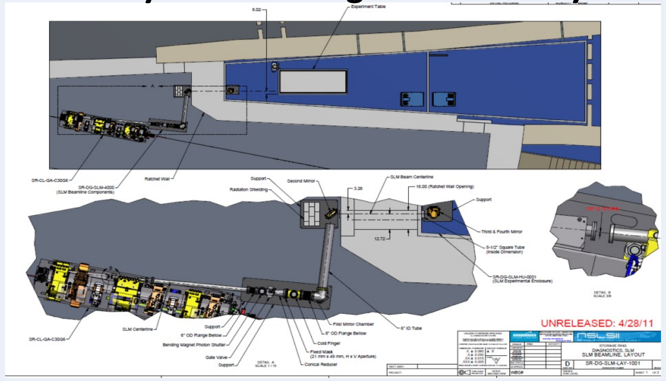
We explore the consequences of sampling interval errors of 2, 5 and 10 ps. In other words, while the first interval is kept constant at 50 ps, the second interval is stepped from 50 ps to 52 ps, 55 ps and 60 ps. The results are shown. We see that the amplitude errors caused by sampling interval errors increase significantly beyond 2 ps, but they are all more accurate than achievable with a single ADC.

Electron Crabbing Angle Measurements

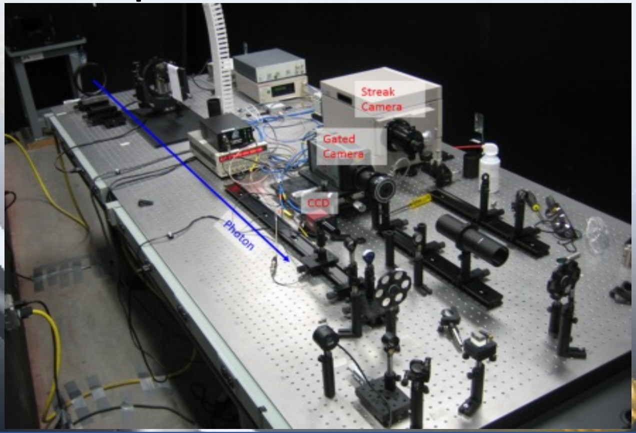
- Electron Crabbing angle can be directly measured using a synchrotron light monitor with streak camera at a location TBD in the electron Storage Ring. Principle was demonstrated KEKB. Challenge is that this has not been done at BNL, different parameters at EIC.
- A cooled mirror will direct the visible portion of synchrotron radiation to an enclosed light transport, then to an optical table in a service building.

ESR synchrotron light monitor design generally based on NSLS-II SLM

NSLS-II Synchrotron Light Monitor layout



NSLS-II Optical table with Streak camera



- Operational strategy for the measurement:
- Since there is no room for an SLM in the IR, the electron crabbing angle cannot be directly measured in the IR during operations. It can be measured elsewhere in the ESR during a studies mode.
- With the crabbing cavity turned on, and the decrabbing cavity turned off, the crab tilted beam will precess around the ring. A SLM will be located in the ESR lattice (away from the IR) at a location chosen with a large angle to optimize the measurement.
- When the decrabbing cavity is turned on (during normal operations), there should be no residual electron crabbing angle outside of the IR.
- Plan to start working soon with NSLS-II colleagues to determine electron bunch crabbing angle measurement capability using ESR lattice and beam parameters.

Crab cavity bunch tilt angles measured at KEKB

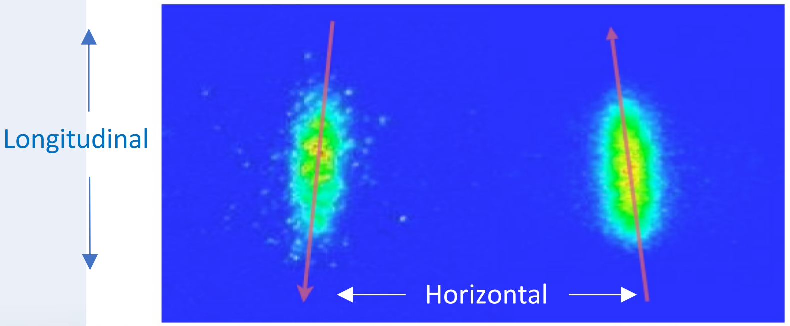


Figure 6: Images taken by streak cameras, which locate as Fig. 2, show tilt of the bunches in the LER (left) and the HER (right)[12].

Compensation of the Crossing Angle with Crab Cavities at KEKB, Abe et al, 2007

Hadron Crabbing Angle Measurements

Crabbing angle near IP determined by different degrees of BPM signal distortion depending on the tilt angle, the zero-crossing time difference is approximately proportional to the tilt angle.

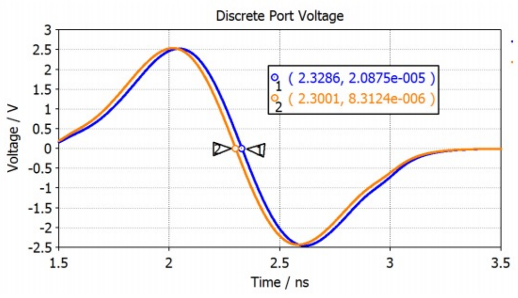


Figure 4: Particle Studio output for the two, opposite, horizontal PUEs when using a 60 mm diameter BPM with 10 mm diameter PUEs with a simulated crabbed bunch input described in Fig. 3.

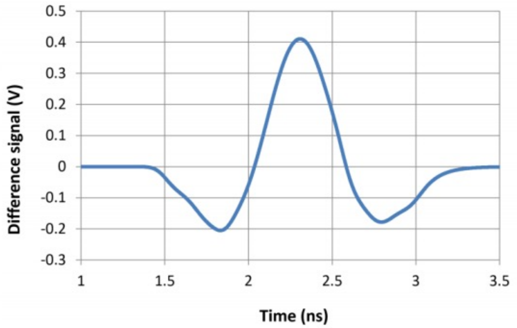
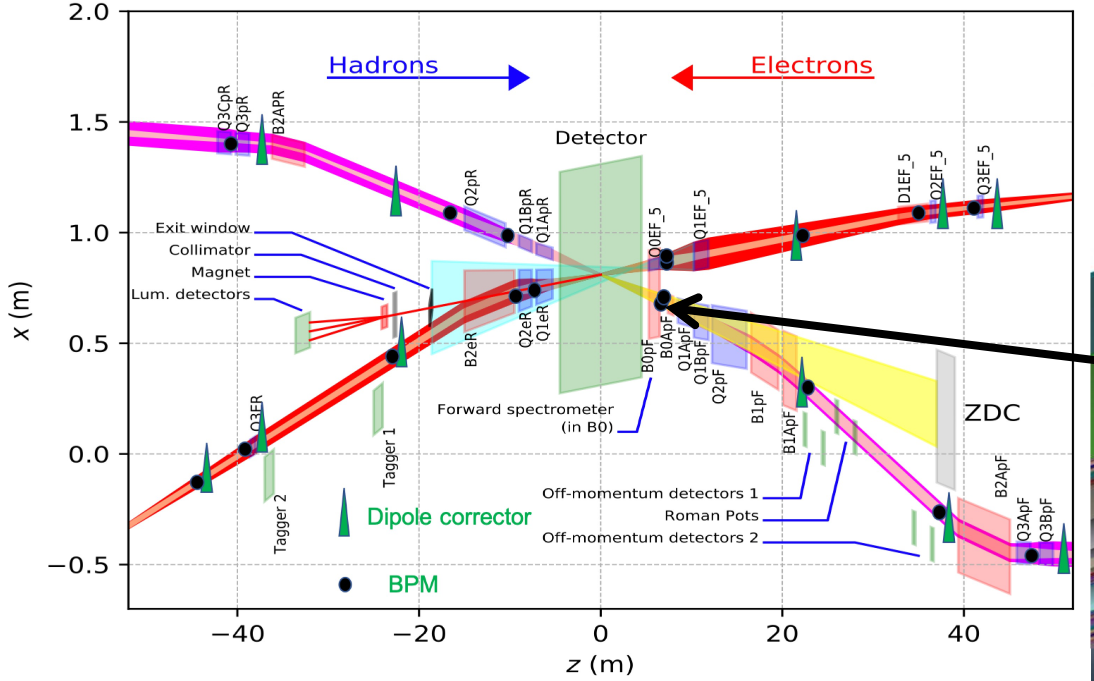


Figure 5: Difference signal obtained by using the simulation output shown in Fig. 4.

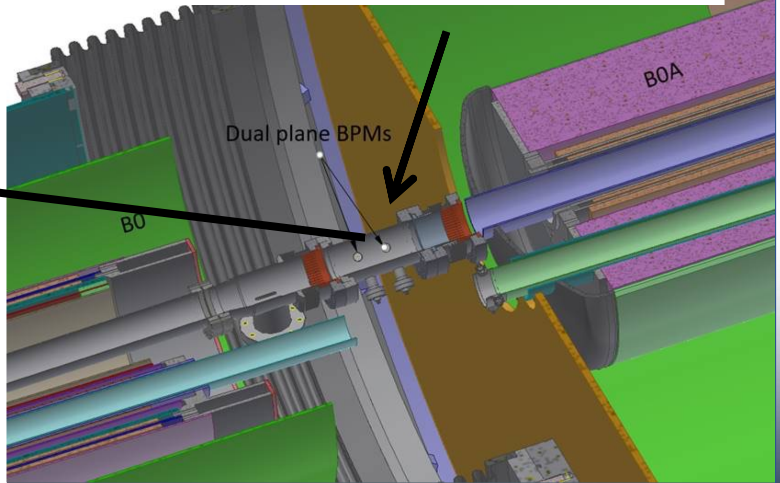
Concept by P. Thieberger
IPAC2018-WEPAF018

Concept has not demonstrated yet. Due to sensitivity to long cable thermal effects, considering using a fast differential signal splitter in reverse, as combiner, close to the BPM



In the space between B0pF and B0ApF the horizontal BPM buttons should see the maximum tilting of the bunch, (crabbing angle 12.5 mrad.) Bending magnets and drifts behave alike with respect to crab rotations.

Proposed location between B0pF & B0ApF



A Head-tail monitor (stripline pick-up) will be installed in the HSR somewhere outside of the IR that can measure hadron bunch tilt angle with the de-crabbing cavity turned off.

Successful test at the SPS:

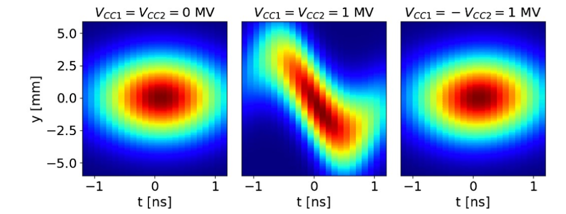
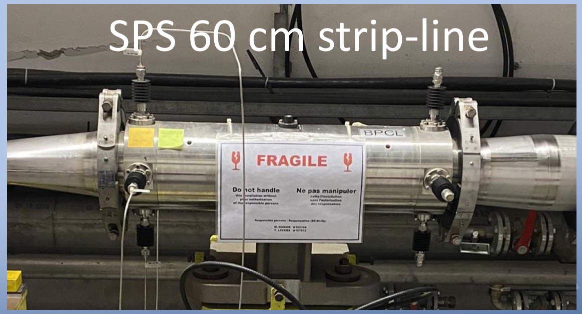


FIG. 3. Intra-bunch motion from three different cases measured with the HT monitor. Left: crab cavities switched off (voltage = 0). Center: synchronous crabbing with both cavities in phase corresponding to $V_{CC} \approx 2$ MV total voltage (V_{CC1} = V_{CC2} = 1 MV). Right: cavities in counterphase, corresponding to residual $V_{CC} \approx 60$ kV total voltage.

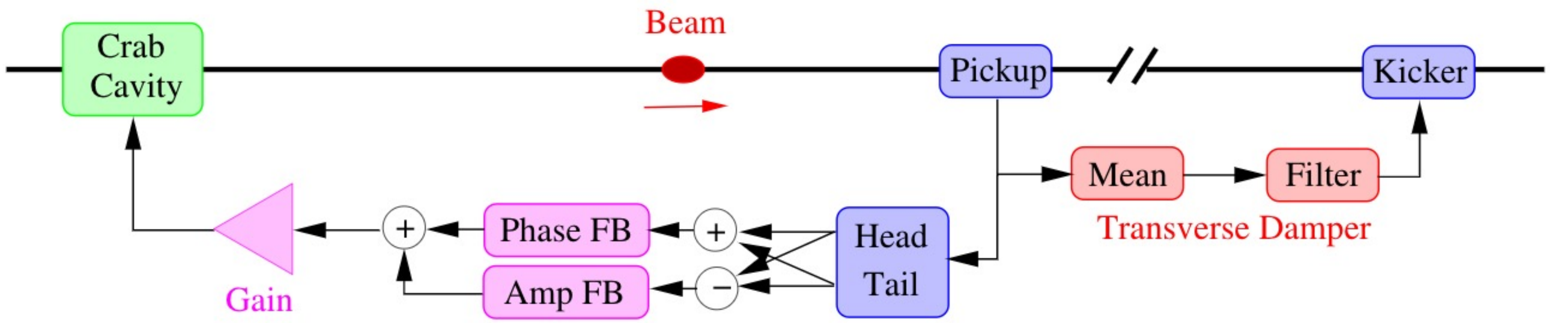


R. Calaga et al. PRAB 24 062001, June 2021

Hadron Crabbing Angle - Residual Measurement

Need crabbing angle residual (noise) measurement, located someplace away from the IR

- Purpose is to reduce emittance growth
- A dedicated feedback system could mitigate crab cavity noise effects. A similar system is planned for the HL-LHC.



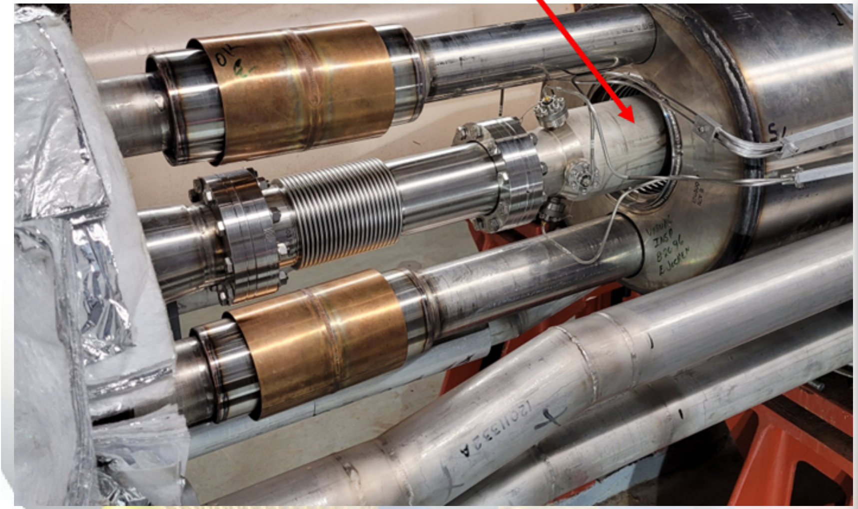
- The bunch head and tail position would be extracted from the pickup signal. The head/tail Δ and Σ estimate the bunch tilt and offset (amplitude and phase noise respectively).
- Themis Mastoridis has conducted simulations of such a system for the EIC HSR to study its potential performance and limitations.
- The performance of the system will greatly depend on the pickup precision, location, and additional technical specifications (signal processing/equalization, longitudinal motion effect, etc).
- The pick-up resolution needed for EIC HSR: TBD
- Type of pick-up under discussion (electro-optical?), considering multiple pickups.
- Potential collaboration topic with CERN.

T. Mastoridis, K. Smith, et al.

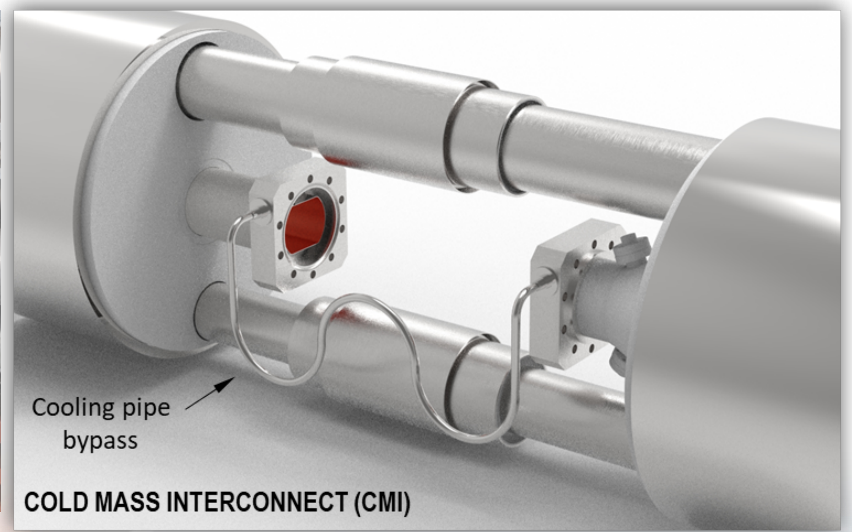
New Hadron Ring BPMs

- To avoid heating of the cryogenic signal cables due to the shorter, more intense hadron bunches, the existing RHIC stripline BPMs will be shielded to minimize impedance.
- 279 new button type cryo-BPMs will be installed in the hadron ring adjacent to the shielded strip-line BPMs

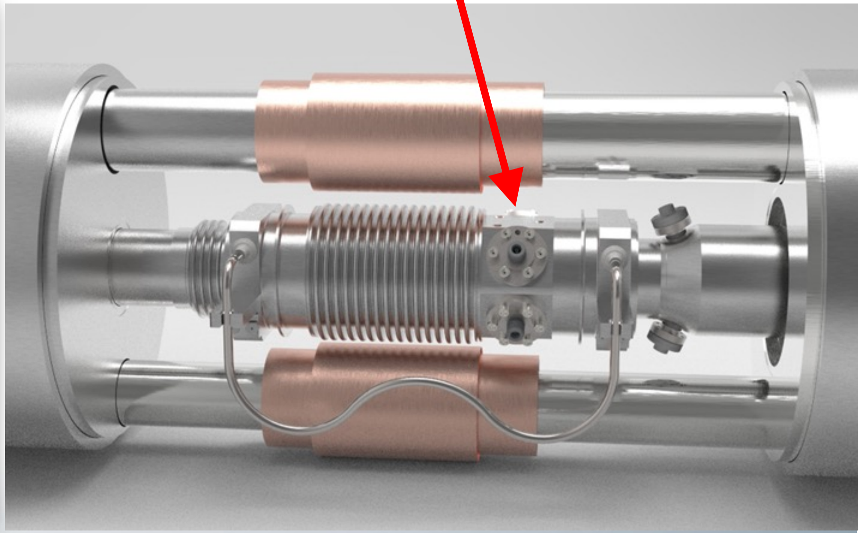
Existing RHIC cryo-interconnect showing existing stripline BPM



Existing interconnect bellows removed, new flanges & cryo cooling bypass



New interconnect bellows with integrated button BPM and cryo-cooling bypass



Pictures & 3D models from C. Hetzel

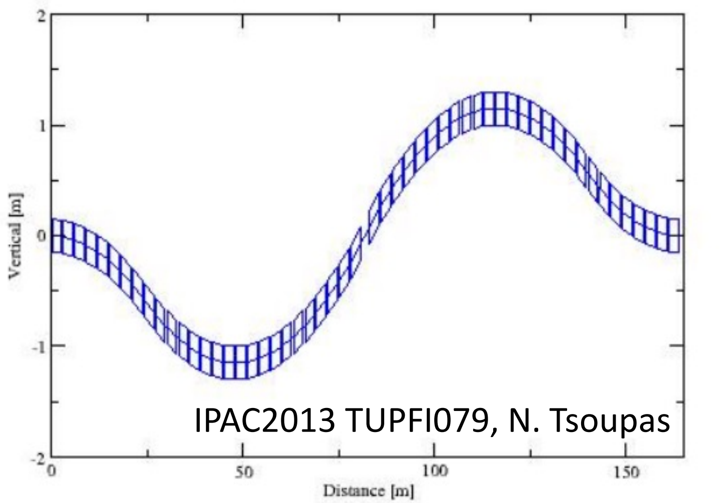
New Hadron Ring BPMs - operations with large radial offset, why?

- Hadrons and electrons must circulate in their respective storage rings with the same revolution period, 12.8 us.
- The electron beam is highly relativistic over the entire energy range of 5 to 18 GeV, so the electron revolution period is practically constant.
- In contrast, the hadron relativistic speed varies significantly over the proton energy range of 100 to 275 GeV.
- To compensate for speed difference, a radial offset is used in the hadron storage ring to change the circumference path length.

Energy (GeV)	Circumference (m)	Change in circumference (mm)	Change in average radial offset (mm)	Change in maximum radial offset (mm)
100	3,833.7506	-73.4	-11.7	-20
133	3,833.8240	0.0	0.0	0.0
275	3,833.8971	73.4	11.7	20

- The radial shift will be greatest (~20 mm) near the cryo-BPMs (horizontal aperture radius of 32 mm) located near the horizontal focusing quads.

- An alternative solution to operate without large radial offsets was to install a 164 m delay line in a warm region, with ~1.5 m displacement, and moveable magnets.
  - Determined to be not feasible
    - Not enough space in the existing RHIC tunnel
    - Overly expensive



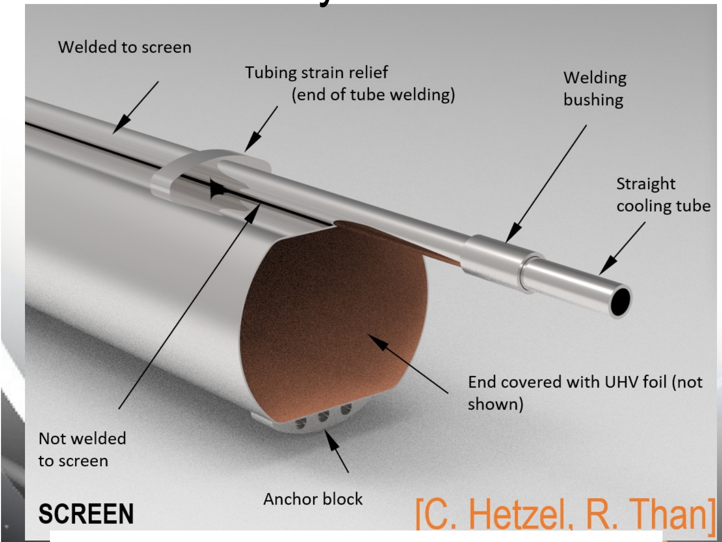
IPAC2013 TUPFI079, N. Tsoupas

New Hadron Ring BPMs – button pick-up design

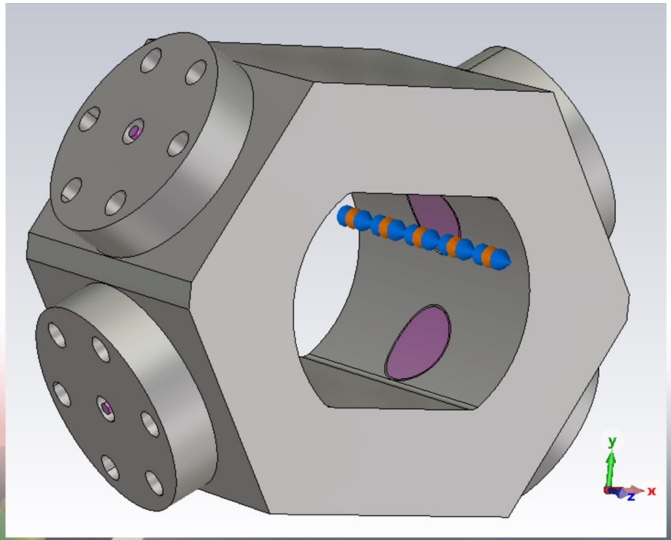
- The new pick-up design considerations:
    - Operations with large radial offset at store
    - Power deposited in the buttons
    - Signal levels to meet performance requirements (20 um resolution, average over 1 second during store)
    - Dynamic range of ~ 85 dB;
        - long 125 cm RMS, 5 nC gold pilot bunches at injection
        - short 6 cm RMS, 30 nC bunches during store with large radial offset.

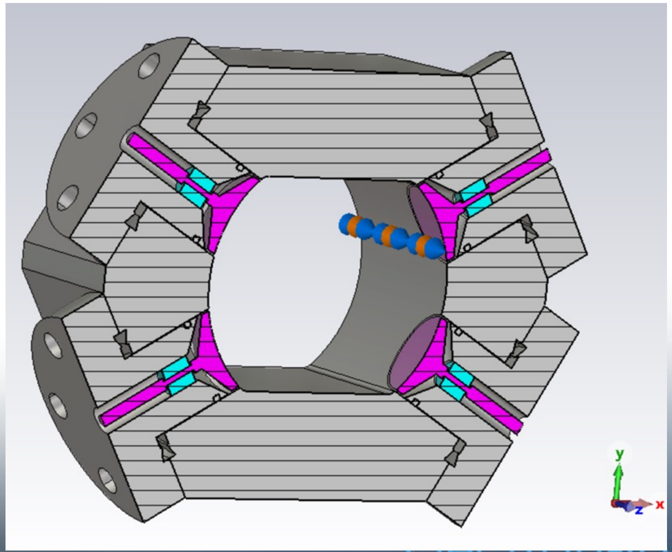
The latest HSR BPM pick-up design has 20 mm diameter buttons, located ~ 30 degrees rotated up and down from the horizontal plane, in a 64 x 50 mm aperture that matches the adjacent beam sleeve to minimize impedance.

HSR actively-cooled screen



69 mm horizontal aperture reduced to 65 mm; vertical aperture of 50 mm





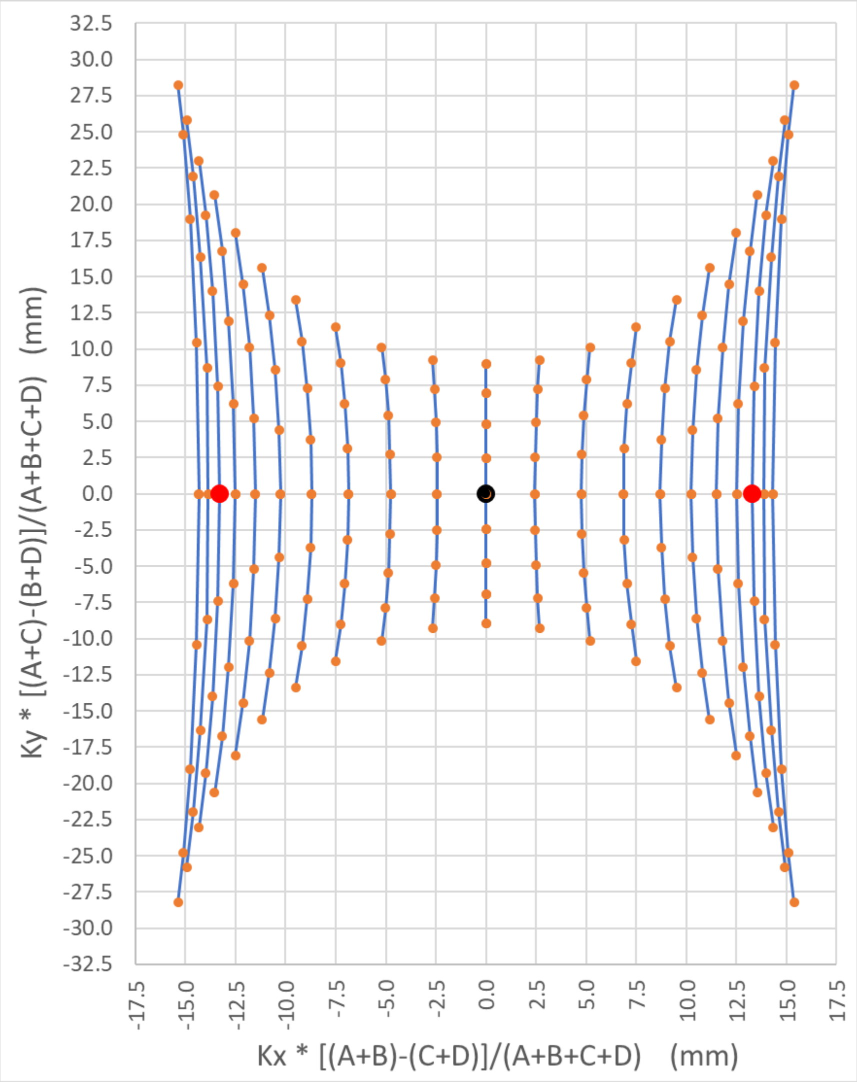
New Hadron Ring BPMs – BPM pick-up design

Pincushion distortion, uncorrected:

Result of Particle Studio simulations carried out for 55 beam positions from X = 0 to 25 mm and Y = 0 to 10 mm in 2.5 mm steps, to determine the corresponding signal peak amplitudes.

Plotted are the positions calculated by using the linear terms only and adjusting the coefficients to provide correct coordinates for approximately centered beams.

The red dots correspond to X = ± 20 mm
beam positions showing the effect of the strong pincushion distortion

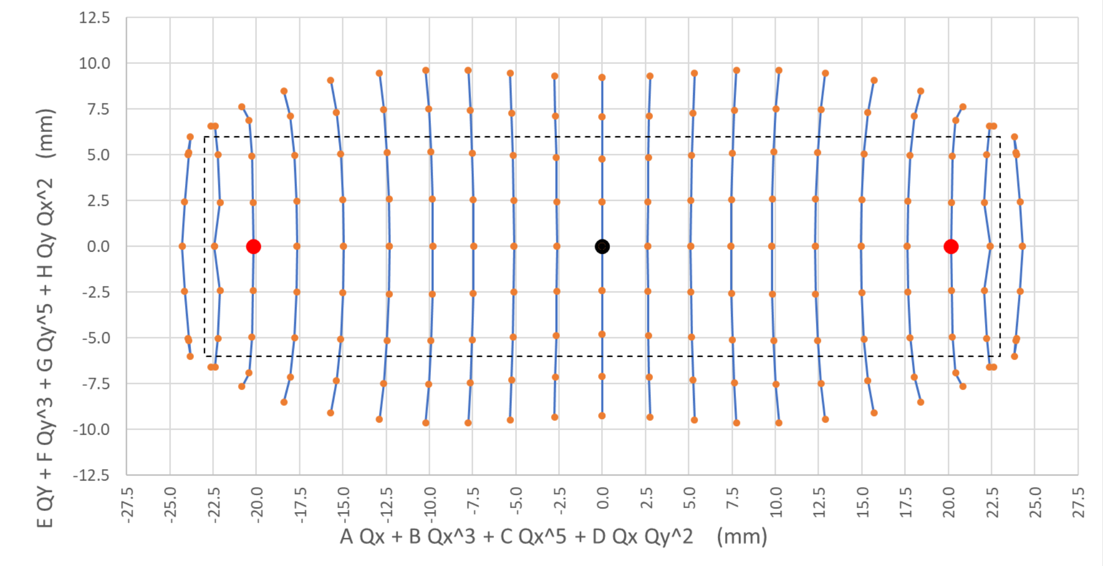


P. Thieberger

P. Thieberger

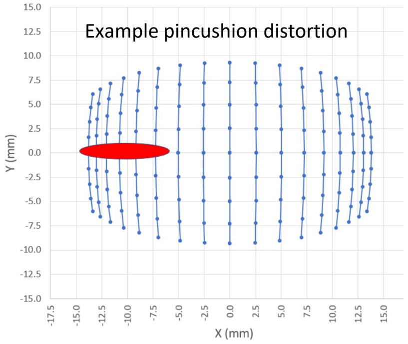
New Hadron Ring BPMs – BPM pick-up design

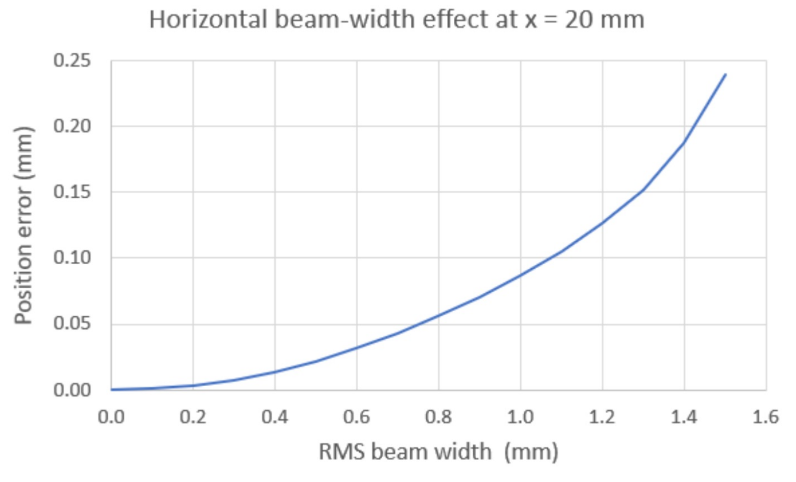
- Corrected positions obtained by linearizing the data with fifth order polynomials. The points used in the least square procedure that determined the optimal coefficients are the ones inside the dotted line rectangle (+/- 23 mm horizontal, +/- 6 mm vertical)



Position measurement correction due to bunch shape

- Due operations with large radial offsets
  - (~20 mm) near the horizontal focusing quads.
- And to the relatively large transverse bunch size aspect ratio:
  - Tall bunch at the horizontally focusing quads
  - Wide at the vertically focusing quads
- Will likely need to introduce an added correction factor based on transverse bunch shape
  - Consider using IPM transverse beam size measurement data in BPM correction algorithm.



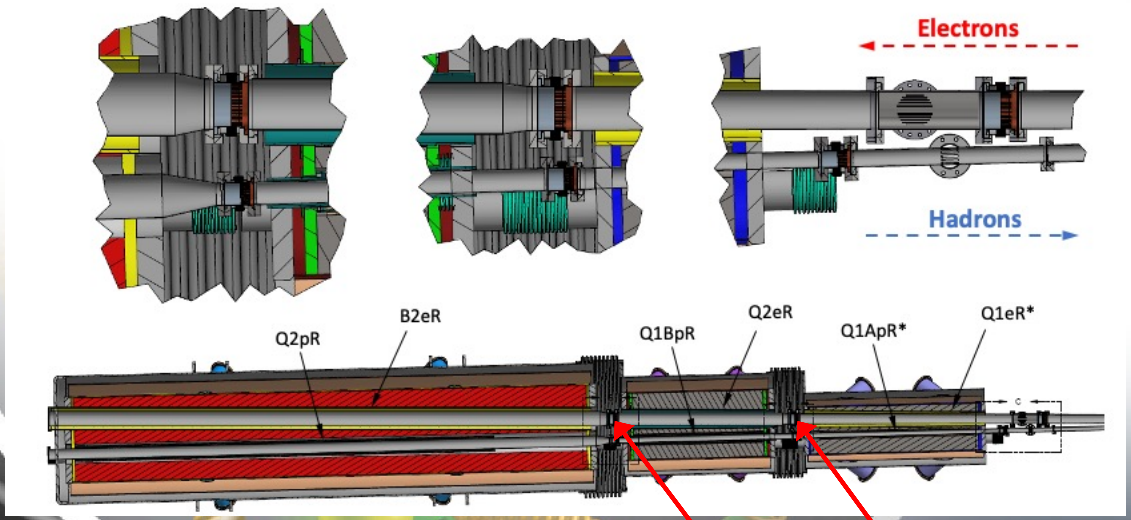


Interaction Region BPM Pick-ups

- Large diameter e-BPM pick-ups in the electron rear region present challenge for 1 um average resolution position measurements.
  - Q1eR (~7.3 m from IP) 56 mm radius (4.4” diameter) in cryostat
  - Q2eR (~9.3 m from IP) 64 mm radius (5” diameter) in cryostat
  - DS of B2eR (22m from IP) 80 mm radius (6.3” diameter)
  - Q3eR (38 m from IP) 80 mm radius (6.3” diameter)

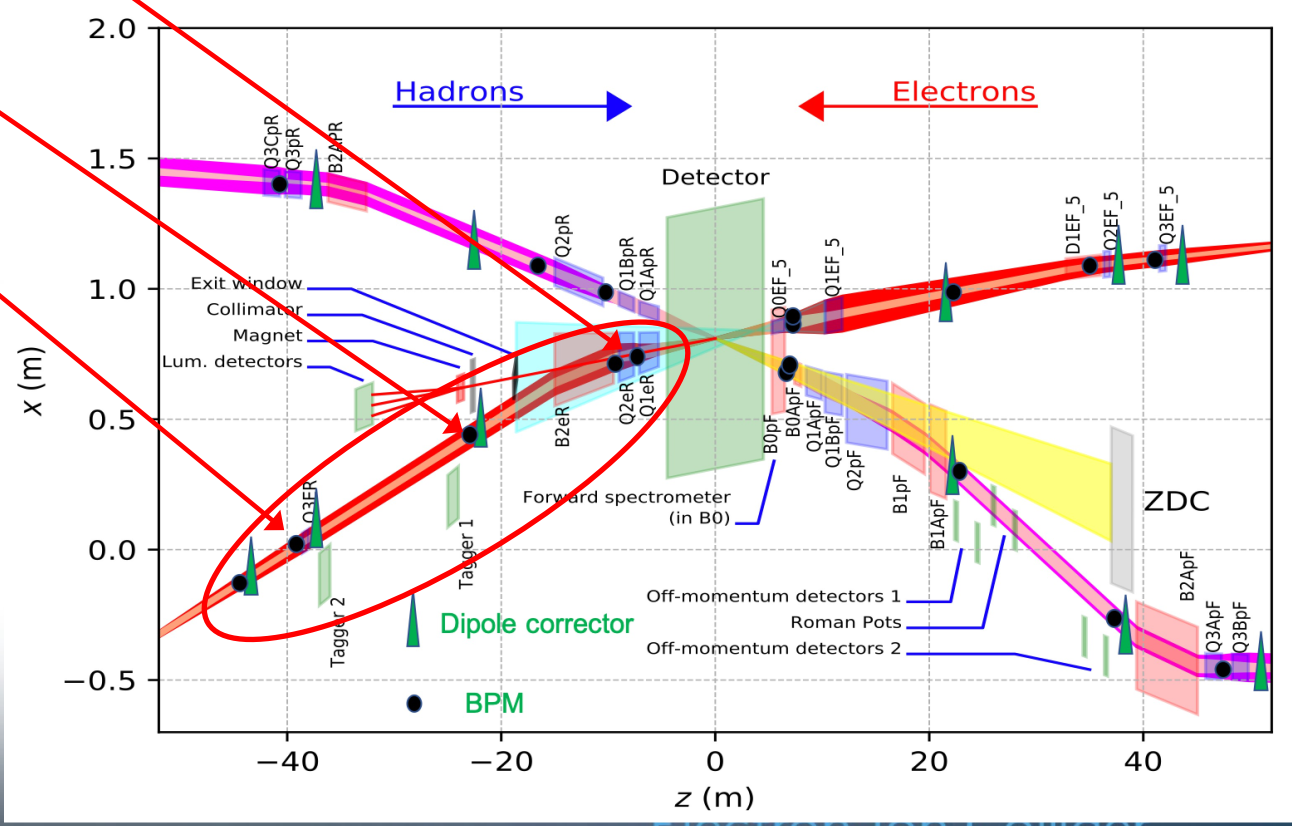
- Relatively large radial offsets in the hadron BPMs near the IP also present challenge for quality measurements, performance requirements TBD.

Rear Side Cryostat



Q2eR BPM

Q1eR BPM



Strong Hadron Cooling – General overview

- Basic cooling principle:
  - In the modulator, the proton bunch Schottky noise pattern is imprinted on the electron bunch
  - In the kicker, the amplified electron bunch pattern used to cool the same part of the proton bunch that was imprinted in the modulator.

SHC facility cartoon layout

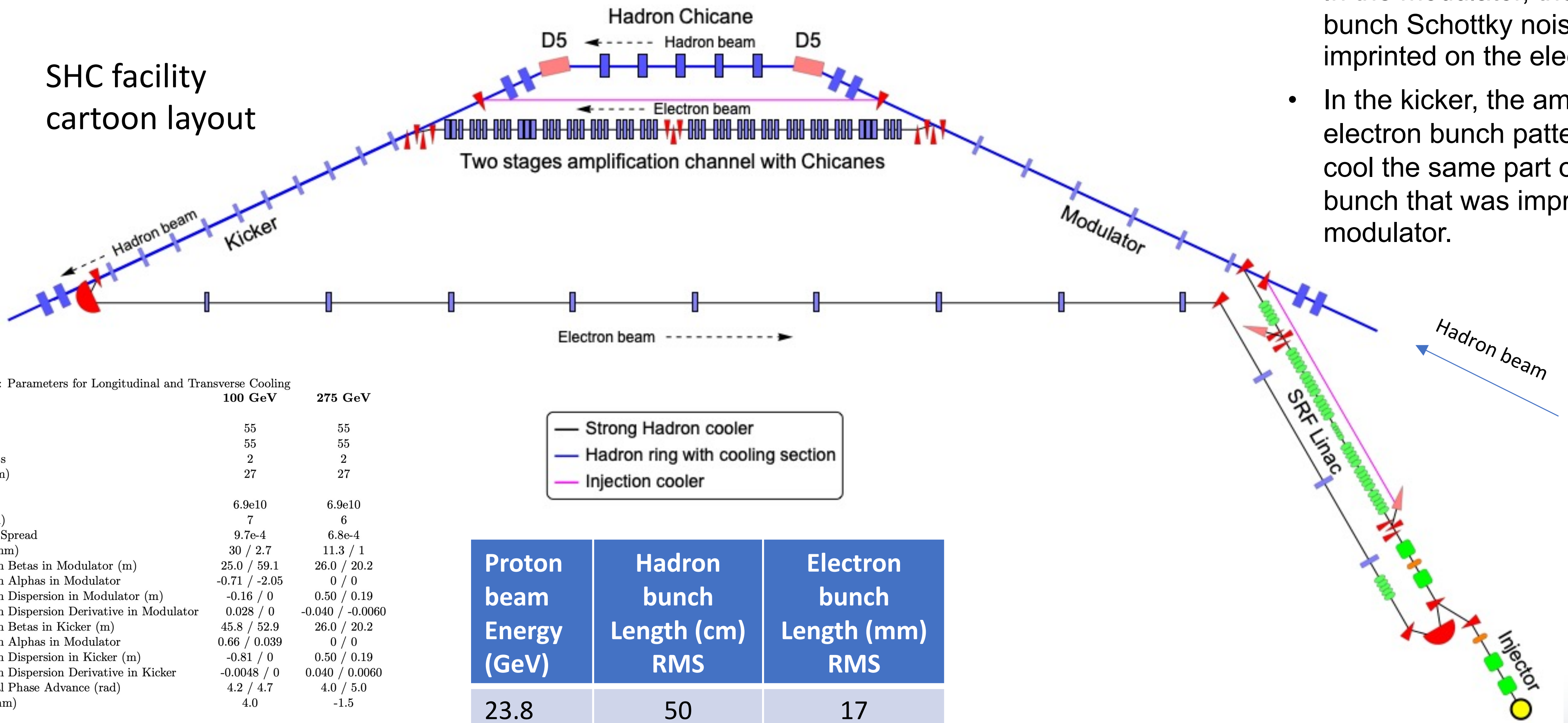


Table 1: Parameters for Longitudinal and Transverse Cooling

Case	100 GeV	275 GeV
Geometry		
Modulator Length (m)	55	55
Kicker Length (m)	55	55
Number of Amplifier Drifts	2	2
Amplifier Drift Lengths (m)	27	27
Proton Parameters		
Protons per Bunch	6.9e10	6.9e10
Proton Bunch Length (cm)	7	6
Proton Fractional Energy Spread	9.7e-4	6.8e-4
Proton Emittance (x/y) (nm)	30 / 2.7	11.3 / 1
Horizontal/Vertical Proton Betas in Modulator (m)	25.0 / 59.1	26.0 / 20.2
Horizontal/Vertical Proton Alphas in Modulator	-0.71 / -2.05	0 / 0
Horizontal/Vertical Proton Dispersion in Modulator (m)	-0.16 / 0	0.50 / 0.19
Horizontal/Vertical Proton Dispersion Derivative in Modulator	0.028 / 0	-0.040 / -0.0060
Horizontal/Vertical Proton Betas in Kicker (m)	45.8 / 52.9	26.0 / 20.2
Horizontal/Vertical Proton Alphas in Modulator	0.66 / 0.039	0 / 0
Horizontal/Vertical Proton Dispersion in Kicker (m)	-0.81 / 0	0.50 / 0.19
Horizontal/Vertical Proton Dispersion Derivative in Kicker	-0.0048 / 0	0.040 / 0.0060
Proton Horizontal/Vertical Phase Advance (rad)	4.2 / 4.7	4.0 / 5.0
R56 in Proton Chicane (mm)	4.0	-1.5
Electron Parameters		
Electron Bunch Charge (nC)	1	1
Electron Bunch Length (mm)	12	8
Electron Peak Current (A)	~ 10	~ 15
Electron Supergaussian Order	4	4
Electron Fractional Slice Energy Spread	1e-4	1e-4
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Horizontal/Vertical Electron Betas in Modulator (m)	86.6 / 14.1	64.1 / 11.4
Horizontal/Vertical Electron Betas in Kicker (m)	49.8 / 10.0	16.5 / 2.0
Horizontal/ Vertical Electron Betas in Amplifiers (m)	2.4 / 2.4	0.50 / 0.50
R56 in First Electron Chicane (mm)	-11.7	2.5
R56 in Second Electron Chicane (mm)	-11.7	2.5
R56 in Third Electron Chicane (mm)	13.8	-6.3
Cooling Times		
Horizontal/Vertical/Longitudinal IBS Times (hours)	2.0 / 4.0 / 2.5	2.0 / 71 / 2.9
Horizontal/Vertical/Longitudinal Cooling Times[2] (hours)	1.6 / ∞ / 1.8	0.8 / 2.1 / 1.2

Proton beam Energy (GeV)	Hadron bunch Length (cm) RMS	Electron bunch Length (mm) RMS
23.8	50	17
100	7	12
275	6	8

Strong Hadron Cooling - relative longitudinal alignment

W. Bergan, E. Wang

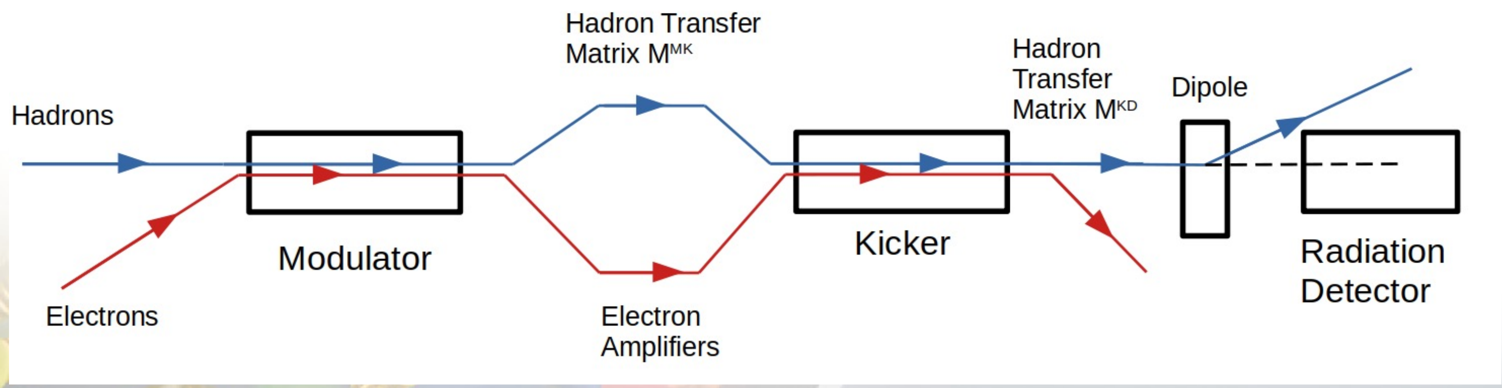
Instrumentation needed:

- Co-propagate the protons and electrons (transverse & longitudinally) in the modulator and kicker
  - Need longitudinal electron-hadron alignment of ~1 um between modulator and kicker
    - Source of longitudinal alignment error can be caused by a change in path length difference due to magnet field ripple

Simulations are underway to find a relative longitudinal alignment measurement solution (W. Bergan, M. Blaskiewicz, G. Stupakov, et al.)

<u>Latest approach:</u>
Try to utilize the feature that the proton beam will have a Schottky signal which will get smaller during the cooling process.
Presently exploring this hadron Schottky "signal modification" measurement as a diagnostic.

There is small difference in the synchrotron light power emitted from the hadron beam after the kicker (downstream of a dipole) that may be able to be measured.



Simplified cooling diagram showing hadron synchrotron light radiation detector.

Strong Hadron Cooling - relative longitudinal alignment

Proposed strategy:
Integrate the hadron synchrotron light signal only during portion of the central hadron bunch being cooled.
For this simulation, integration over gated intervals for 1 second, with 11 ns bunch spacing.

100 GeV; central 12 mm of of 7 cm hadron bunch being cooled, need 40 ps integration time per bunch
275 GeV; central 8 mm of of 6 cm hadron bunch being cooled, need 27 ps integration time per bunch

Beam Energy (GeV)	Radiation from core nW/m^2	For 10% measurement resolution nW/m^2	Synch light wavelength + 10% BW (um)	Fractional change in Synch light intensity (%)	Number of signal photons e6	Number of background photons e6	Signal to Noise	Detector area mm^2	Sensor thermal cooling: Type (temp), background
100	100	0.550	30	5.5	8.3	1500	210	100	LH (4.2K), 2e-48W/m^2
275	18,000	110	3	6	1.6	270	99	1	LN2 (77K), 5e-22W/m^2

Challenge:
Need to find cooled infrared detectors at with sensitivity at 3 and 30 microns that can be gated to measure only during hadron bunch core (10's of ps)

Simulations of measurement configuration variations continue; we may be able to reduce the signal wavelength to make it easier to find sensors to measure these small variations in light power.

W. Bergan, E. Wang, et al.

Summary

- There are a variety of instrumentation challenges at the EIC:
  - Those associated with a project with a relatively large and diverse scope
  - Pandemic related complications
  - Specific technical challenges
- Other instrumentation challenges not mentioned include:
  - Electro-optic longitudinal bunch shape monitor design (plan to test prototype during next RHIC run)
  - Machine protection strategies with 3 rings running simultaneously & at the cooler
  - BPM measurement drift compensation due to thermal effects
  - and more….
- There are a number of potential topics for collaborations with other institutes

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Thank you for your attention!